Volcanic Ash Contamination of High Voltage Insulators

Revising Insulator Design to Aid the Electrostatic Repulsion of Volcanic Ash

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1. INTRODUCTION

Ashfalls from volcanic eruptions can pose a considerable risk to electric transmission and distribution networks. Dry ash is non-conductive [1] and unlikely to cause an insulator flashover; but it is of concern when the ash becomes damp/wet through light rain, dew, and fog. Volcanic ash is the signature of a volcano; all volcanoes have slightly different volcanic ash. During an eruption the ash absorbs charged halogens and molecules into its surface which dry to become soluble salts [1]. When the ash becomes wet, these trapped soluble salts dissolve in the water to form a conductive channel. This can result in insulator flashover.

Current insulator cleaning methods are exceedingly labour intensive and can only occur once a volcanic eruption has finished. Linemen are required to manually clean each and every insulator. This is a very time consuming task and may result in a lengthy downtime for the affected transmission line [2]. A self-cleaning insulator would vastly improve the current situation. Not only would the insulators be less susceptible to the build-up of ash, the effort and money required to manually clean the insulators would be substantially reduced. Only transmission lines potentially susceptible to volcanic ash contamination would need to be retrofitted, with either new insulators, or to modify existing insulators to improve their self-cleaning abilities and assist the natural cleaning of heavy rain.

2. THEORY OF OPERATION

2.1 Hypothesis

Previous research found that ash was able to be shed from an insulator weather shed in significant quantities at approximately 160kV [4]. The removal of ash is through electrostatic repulsion [4]. Ash particles become charged when subjected to high strength electric fields; these charged particles are repelled by the alternating supply voltage, once the particle possesses enough charge to overcome the weight of the ash particle.

In this paper, it is assumed that by increasing the electric field strength on the top surface of the insulator weather shed, more ash particles would be electrostatically charged and shed from the insulator. It is also proposed that increasing the electric field strength would result in a lower ash removal onset voltage; with the aim to reduce this voltage to at or below the operational voltage of the insulator.

2.2 Background

2.2.1 Electrostatic Repulsion

Coulomb's Law (electrostatic repulsion/attraction) states two particles will either be attracted to or repelled from one another if their charge polarities are opposite or the same respectively [9].

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2} \quad (1)$$

where Q is the charge
r is the charge separation

2.2.2 Corona Charging of Particles

High voltage is applied to a discharge electrode (the caps of the insulators), which results in a corona discharge. The polarity of the discharge is positive or negative and is determined by the polarity of the discharge electrode [7]. The free electrons crash into molecules resulting in the formation of positive ions and further free electrons which leads to an electron avalanche. Both types of corona create an electron avalanche [10]. During positive corona, liberated electrons are accelerated towards the electrode, while in negative corona the electrons are repelled and decelerate the further they get from the electrode [10]. The electrons now do not possess enough energy to form positive ions and free electrons. Instead they are captured by polar molecules to produce negative ions (negative corona) [10].

2.2.3 Pin and Cap Insulators

A three disc cap and pin suspension insulator string was chosen for experimental testing. This type of insulator is commonly used throughout the world, due to their ease of manufacture, reliability and they are generally quite resistance to environmental factors such as UV radiation, and salt deposits [5]. Although this type of insulator is often replaced by composite insulators which are lighter and easier to install, it is proven technology and suitable for installation where robustness and reliability is essential.

High voltage insulators are designed to meet both electrical and mechanical requirements; the insulators must isolate the pylon/pole from the high voltage conductors and provide mechanical strength to account for the weight of the hanging conductor [5]. The skirt (weather shed) of the insulator provides a large creepage distance (the distance along an insulating surface between two conductive electrodes) and electrical isolation between the conductive cap and pin [5].

3. MODELLING/DESIGN

The finite element modeling (FEM) software package ElecNet [6] was used to model the electric fields encircling the three disc insulator string.

A three disc 33kV insulator string model was developed as shown in Figure 1a. The developed model was used as a base case to compare how altering the shape/design of high voltage insulators affects the surrounding electric flux lines, which in turn affects the electric field strength. Parameters relating to the materials used in the model were researched to enable accuracy in the developed model; these parameters can be found in Appendix A.

The above model was solved using FEM to produce an electric field diagram as shown in Figure 1b. The insulator weather shed has minimal effect on the electric field and is installed purely to increase the creepage distance of the insulator. High electric field strengths occur between the cap and the pin as the electric flux lines squeeze through the dielectric materials of the glass insulator and the aluminous/bitumen cement, which bonds the glass weather shed to the cap and pin. The electric flux lines spread out quickly after exiting this section causing the electric field strength to reduce abruptly. The model predicts very low electric field strengths across the top surface of the insulator weather sheds, thus minimal quantities of ash are predicted to become electrostatically charged and repelled.

The proposal developed was to install a small metal disc on the underside of the weather shed around the insulator pin. This had the effect of increasing the surface area of the floating pin electrode. The electric flux lines cannot travel through a floating electrode and are required to traverse the disc insert to obey Gauss's Law [9]. This stops the electric flux lines from spreading out as abruptly and diverts them through into the glass weather shed, which has the effect of increasing the field strength on the weather shed's surface. The modified FEM model of Figure 1c shows an increase in the electric field strength across the surface of the weather shed. It is predicted that higher quantities of ash should become electrostatically charged and repelled from the insulator weather shed.

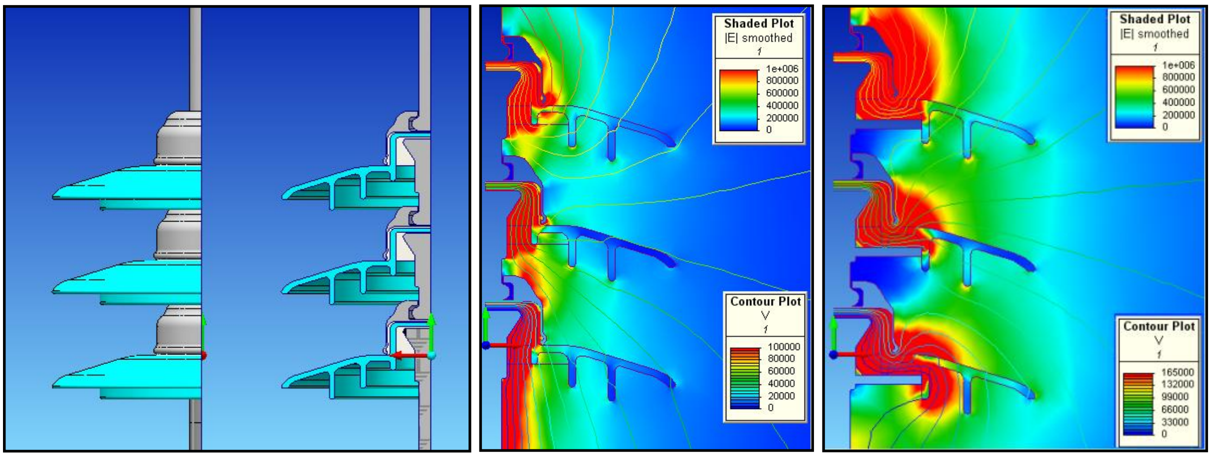

Figure 1: a) Developed Insulator ElecNet Model; b) Unmodified Insulator FEM Results; c) Modified Insulator FEM Results

4. DISC INSERT DESIGN

The disc inserts were machined from 5mm thick aluminum plate. Silicon glue was used to hold the disc inserts in place underneath the insulator weather shed. Silicon glue has similar dielectric properties to the glass and aluminous/bitumen cement already contained within the insulator and should have no effect on the electric fields associated with the insulators. Figure 2 shows the CAD model the disc was machined to match and how the disc insert is installed into a standard insulator. The disc was made in two parts to enable easy installation.

Figure 2: a) Standard Insulator; b) Modified Insulator with Disc Insert Installed; c) CAD Design of Disc Insert

5. EXPERIMENTAL SETUP

The experimental set up shown in Fig. 3 allowed for up to 330kV to be placed across the insulators to experimentally test flashover voltages and ash removal.

When determining the associated flashover voltage; the voltage was ramped up at a steady pace until flashover occurs. Ash removal onset voltages were determined visually, being the voltage at which shedding of ash was first observed.

To be consistent while experimentally testing the ash removal characteristics of both insulator strings, the voltage was steadily ramped up to 100kV and held at this voltage for one minute to allow a sufficient time for the removal of ash. The voltage was then ramped down to zero and the system isolated.

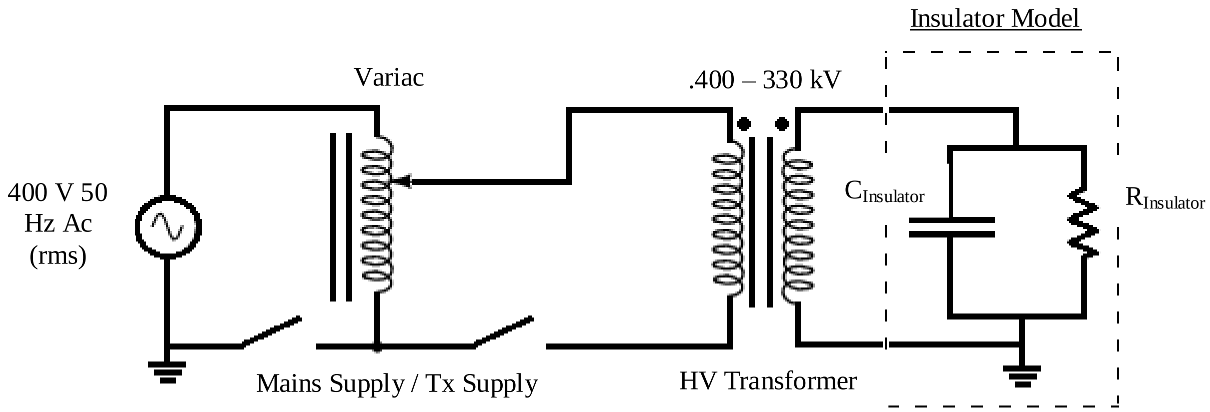

Figure 3: High Voltage Test Setup

6. RESULTS

6.1 Flashover Voltage of Insulator String

Flashover voltage tests were undertaken on both a standard and modified insulator string. The results are presented in Table 1. All tests were undertaken sequentially to eliminate variance caused by environmental factors such as temperature and humidity.

Table 1: Flashover voltage of a standard and modified insulator string

	Test 1 (kV)	Test 2 (kV)	Test 3 (kV)
Standard Insulator String	194	198	201
Modified Insulator String	201	201	201

The flashover voltage of the modified insulator string did not vary, while the flashover of a standard insulator string fell within an 8kV range. The modified insulator string flashed over between the inserts creating three smaller arcs, whereas the standard insulator string flashed over between the top insulator cap and the bottom insulator pin.

6.2 Increased Level of Corona at 100kV

It was noticed that corona was more prevalent on the modified insulator string. The corona formed a distant band around the top of the insulator weather shed. The FEM model calculated an extremely high electric field at this location. A decibel meter was used to measure the increase in noise. This is shown in Table 2. Testing of emitted noise was undertaken at 100kV because at lower voltages the emitted noise was negligible.

Table 2*: Insulator Corona Noise*

	Emitted Noise (dB)
Standard Insulator String	53
Modified Insulator String	60

6.3 Ash Removal

Three different ash layer thicknesses were experimentally tested; moderate ash coverage (~2.0mm), heavy ash coverage (~1.0cm), and light ash coverage (≤1.0mm). The thickness of ash was found to dramatically alter the effectiveness of an insulator string's ability to self-clean.

6.3.1 Moderate Ash Coverage

At 100kV, the standard insulator string was inefficient at shedding ash with virtually no ash removed. The modified insulator string was able to shed a significant amount of ash, leaving distinct bands clean of ash. Figure 4a shows the results achieved during the one minute test. The longer the system remains energized the higher the quantity of ash removed and the wider the bands clear of ash become. The bands clear of ash could potentially provide enough of a gap between the ash and the insulator cap to prevent a flash over, in the event the ash becomes wet. Ash was removed from the insulator cap outwards in distinct bands; only a small amount of ash was shed from the outer edge of the insulator weather shed.

6.3.2 Heavy Ash Coverage

The removal of ash was considerably less effective with heavy ash coverage. Ash was not removed at all from around the insulator cap as had been the case with the moderate ash coverage testing. Instead, ash was removed from the outer edge of the insulator weather shed. Ash was not removed in bands but at distinct locations around the weather shed. Fig.4b shows a very uneven outer edge around the top weather shed as some areas had ash removed while other areas did not. Heavy ash coverage was only tested on the most effective top insulator as limited quantities of ash were available.

6.3.3 Light Ash Coverage

When a very light (<1.0mm) layer of ash was applied to the insulator string, a considerable amount was able to be removed from all three insulators. Figure 4c shows the clear bands where ash was removed. Virtually all the ash was able to be removed from the top weather shed and about 50% of the ash was removed from the lower weather sheds.

The onset voltage at which ash removal begins is significant; this must be below the operating voltage of the insulator string to enable ash to be removed.

Table 3: Ash removal onset voltage

Ash Coverage	Ash Removal Onset Voltage (kV)
Standard Insulator String	94
Modified Insulator String – Light	53
Modified Insulator String – Moderate	36
Modified Insulator String – Heavy	78

It was extremely difficult to see when the onset of ash removal occurred with a light ash coverage. It is believed that the onset voltage of ash removal with a light dusting is closer to that of the moderate ash coverage onset voltage. The small quantities being removed require a close up view to ascertain the exact ash removal onset voltage.

Figure 4: a) Moderate Ash Coverage; b) Heavy Ash Coverage; c) Light Ash Coverage

7. DISCUSSION

Ash was removed in distinct bands moving from the insulator cap outwards across the weather shed. The resulting ash edge (air-ash boundary) was extremely sharp (vertical) as shown in Fig.5a. Ash located on this air-ash boundary was able to gain sufficient energy to be shed and pulsated off the insulator in thin bands. As ash is shed, the air-ash boundary moves further across the insulator weather shed and the frequency of the pulsing ash removal reduces. High speed camera footage showed the slowing of the ash pulses the further away from the insulator cap.

It is possible that two mechanisms assist the removal of ash. Close in by the insulator cap, strong electric fields exist which cause field charging of the volcanic ash, whereas further away from the insulator cap it is possible that negative ions are created when free electrons formed during corona emissions attach themselves to the halogens salts and molecules trapped within the volcanic ash. Negative corona requires polar molecules which scavenge free electrons to form negative ions (the absorbed halogens and salts and molecules in the ash are highly polar). This could be a reason why the electrostatic repulsion of the ash moves from the insulator cap outwards in distinct bands. Only ash particle located on the air-ash boundary are available for electron attachment and the formation of negative ions. The electric field strength reduces the further out from the insulator cap the boundary moves. The ash would require higher quantities of electron attachment to gain sufficient energy to overcome the weight of the ash particle. Also more electrons are required to account for the reduced electric field. As the ash-air boundary moves out from the insulator cap, the circumference of the band is larger resulting in a lower concentration of free electrons.

The mechanism removing the ash from the insulator weather shed could potentially be working in a similar fashion to an electrostatic precipitator which generally uses negative corona to charge dust particles [11]. However in this case the alternating supply voltage provides the attraction/repulsion of the charged volcanic ash.

Figure 5: a) Close up of Ash-Air Boundary, sharpness (verticalness) of boundary noticeable; b) Frame from high speed camera shows ash removal begins close in by the insulator cap

8. FUTURE INVESTIGATION

A new prototype disc insert should be developed and tested that is molded to sit flush (remove air gap above disc insert) against the underside of the insulator weather shed shown in Fig.6. The FEM model predicts a slight increase in the electric field strength on the top surface of the insulator weather shed. It is believed that this would further lower the onset voltage of ash removal. Live testing should be conducted to ascertain whether ash would settle on top of a modified insulator string. If the ash is repelled as or before it settles on the insulator weather shed this modification could be a simple, cost effective and viable solution to an intermittent problem.

It is still undetermined what part the halogens and absorbed molecules play if any in the electrostatic repulsion of volcanic ash. A valuable study would be to test pseudo ash which has not being doped with halogens and molecules. The quantity of ash shed from the insulators would enable conclusions to be drawn as to what effect the absorbed molecules have on the electrostatic repulsion of volcanic ash.

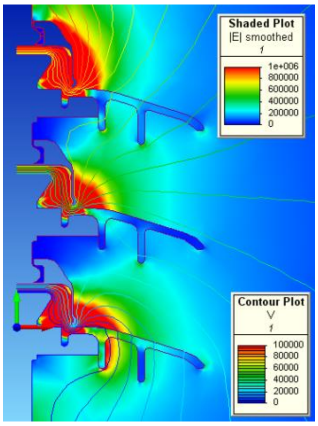

Figure 6: New design disc insert; flush with insulator weather shed

9. CONCLUSION

The aim of the project was to alter the shape/design of a high voltage cap and pin insulator to increase the quantity of ash able to be electrostatically shed. An effective alteration to the insulator was modeled using finite element software (ElecNet) and experimentally verified.
The developed disc inserts effectively reduced the required ash removal onset voltage with moderate ash coverage from ~94kV to ~36kV. This is a significant improvement; however this voltage is still slightly above the operational voltage of the tested insulators (33kV). For this solution to be suitable to be implemented, the onset voltage would have to be lowered by about another 10-15kV, without reducing the flashover level.

The amount of corona discharge at 100kV has directly increased due to the increase in the electric field strength across the insulator weather shed. This could pose potential problems for the insulator and may reduce the insulator's life expectancy as a result of the significant increases in the electric field strength. It is believed that ash is removed due to electrostatic repulsion as a direct result of the increase in the level of corona. Other electrostatic factors may play a role in the removal of ash, but more investigation is required to determine more information.

10. REFERENCES

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APPENDIX A

Material	Relative Permeability	Conductivity (Siemens/m)	Resistivity (Ohm.m)	Relative Permittivity	Thermal Conductivity (W/.(m.C))	Thermal Heat Capacity (J/kg.C))	Mass Density (kg/m3)
Cast Iron	1	10300000	0	1	386	383.1	7200
Glass	1	0.00	0	7	/	/	2520
Aluminum	1	3.8E+07	0	1	204	/	2707
Air	1	0	0	1	0.025	896	1.2
Cement	1	0	0	8	/	/	1500